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(57) Abstract

One of the important considerations in a coded modulation scheme is the bits-to-symbol mapping, which has a significant impact on the overall error rate performance. Bits-to-symbol mappings are described that can achieve different levels of error protection for different classes of information and simultaneously optimize the performance of the different classes.

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SYMBOL MAPPINGS FOR CODED MODULATIONS

BACKGROUND

This invention relates to coded modulation schemes and more particularly to bits-to-symbol mappings for such schemes.

Coded modulations such as multi-level coding or block coded modulation (BCM) can be used to increase the information rate (spectral efficiency) of a communication system without decreasing power efficiency. This increase in the information rate is useful in a communication system in which speech signals are digitized and compressed before being transmitted. Higher compression saves bandwidth, but reproduction quality suffers under adverse conditions in the communication channel. The increased information rate with coded modulation permits less compression to be used, and hence reproduction quality can be improved. A greater information rate, i.e., a greater information capacity, also enables a communication system to accommodate more users.

Multi-level coding schemes, such as BCM, are described in H. Imai et al., "A New Multi-Level Coding Method Using Error Correcting Codes", <u>IEEE Transactions on Information Theory</u> vol. IT-23, pp. 371-377 (May 1977); S. Sayegh, "A Class of Optimum Block Codes in Signal Space", <u>IEEE Transactions on Communications</u> vol. COM-34, pp. 1043-45 (Oct. 1986); A.R. Calderbank, "Multi-Level Codes and Multi-Stage Decoding", <u>IEEE Transactions on Communications</u> vol. COM-37, pp. 222-229 (Mar. 1989); G. Karam et al., "Block-Coded Modulation Using Reed-Muller Component Codes with Multistage Decoding", <u>European Transactions on Communications</u> vol. 4, pp. 267-275 (May 1993); and T. Woerz et al., "Decoding of M-PSK Multilevel Codes", <u>European Transactions on Communications</u> vol. 4, pp. 299-308 (May 1993).

Recent publications on the suitability of BCM for Rayleigh fading channels include N. Seshadri et al., "Multi-Level Coded Modulations for Fading Channels", Proceedings of the Fifth Tirennia International Workshop on Digital Communications (E. Biglieri et al., eds.) pp. 341-352 (1992); N. Seshadri et al., "Coded Modulation with Time Diversity, Unequal Error Protection and Low Delay for the Rayleigh Fading Channel", Proceedings of First Universal Conference on Portable and Mobile Communications pp. 283-287 (Sept. 1992); and N. Seshadri et al., "Multi-Level Block Coded Modulations with Unequal Error Protection for the Rayleigh Fading Channel", European Transactions on Communication vol. 4, pp. 325-334 (May 1993). Multi-level BCM is an attractive scheme for combined modulation and coding, particularly for Rayleigh fading environments where interleaving depth is a crucial factor in determining the bit error rate (BER) performance.

A transmitter using BCM and eight-point phase-shift keying (8-PSK) modulation is shown in Fig. 1, in which a speech or other information source 11 generates a stream of digital data, such as binary bits, that passes to a speech encoder 13. The encoder 13, which may be a code-excited linear predictive coder, transforms the digital data into a plurality of streams i_0, i_1, i_2, . . . of encoded digital data elements, each stream representing a respective subset of the information in the information data stream. In this 8-PSK example, there are three such streams i_0, i_1, i_2, although it will be understood that an M-ary modulation other than 8-PSK, such as 16-PSK or 16-ary quadrature amplitude modulation (QAM), and other than three streams, i, of encoded digital data elements might be used. At least one of the streams of encoded data elements represents information in the speech signal that is more important than the information represented by the other streams.

The streams i_0, i_1, i_2 are provided as inputs to a BCM encoder 14, which includes a plurality of block encoders

15 connected in parallel and a bits-to-symbol mapper 16. The input streams are encoded according to respective block codes C_0, C_1, C_2, yielding respective output streams of codewords comprising respective streams b_0, b_1, b_2 of code symbols, e.g., digital bits. The codes C are called component codes, and have respective rates k/N, where N is the block length and k is the number of input symbols that are encoded in each block of N code symbols. This scheme provides an overall information rate $R = (k_0 + k_1 + k_2)/(N)$ information bits per code symbol. For illustration, let the code C_0 be the most powerful code, followed by the code C_1 and then the code C_2. With such an arrangement, the bit stream i_0 would represent the most important class of information, which may be called Class 0; the bit stream i_1 would represent the next most important class, which may be called Class 1; and the bit stream i_2 would represent the least important class, which may be called Class 2.

Each of the succession of triplets of coded bits $\{b_2b_1b_0\}$ produced by the block encoders 15 is used by the mapper 16 to select a respective one of the constellation of eight 8-PSK symbols according to a predetermined scheme. In this example, b_2 is the most significant bit (MSB) and b_0 is the least significant bit (LSB). A conventional bits-to-symbol mapper uses either natural binary mapping or Gray code mapping. In this way, three N-symbol block codewords generated by the three block encoders 15 are transformed into one modulation codeword, comprising N modulation symbols.

The bits-to-symbol mapper 16 produces a stream of generally complex-valued (I + jQ) modulation symbols that is provided to a symbol interleaver 17, which shuffles the order of the modulation symbols, separating formerly successive symbols in time. Interleaving helps spread the effect of noise and other events in the physical communication channel among the modulation symbols, minimizing the chances that all of the symbols of a codeword

will be affected and taking advantage of the built-in time diversity of the multi-level block code. The stream of interleaved modulation symbols produced by the symbol interleaver 17 is provided to an I, Q modulator 18, which quadrature modulates a carrier signal with those symbols. The modulated carrier signal is transmitted via an antenna.

It will be understood that other components may be included in the transmitter illustrated in Fig. 1. For example, the data streams i may be scrambled before passing to the encoder 14. Also, spectral shaping and amplification may occur at various points. Since such functions are well understood by those of skill in the art and are not necessary to an understanding of Applicants' invention, a description of them is not necessary here.

As described above, the BCM encoder 14 uses the triplets $\{b_2b_1b_0\}$ of coded bits as addresses for the 8-PSK symbols, which may be stored in a memory at locations identified by the addresses. The relationship between the triplets and the modulation symbols is called a "mapping", and typically either natural order binary mapping or Gray code mapping is used. Fig. 2 illustrates a BCM encoder 14 in which C_0 is a (4,1) repetition code and C_1 and C_2 are (4,3) single-parity-check codes, and Fig. 3 illustrates the natural binary mapping of triplets to 8-PSK symbols. In the encoder illustrated in Fig. 2, the block length N of the codes C_0, C_1, C_2 is four, and thus four triplets of block code symbols {111}, {100}, {110}, and {101} are used to select four 8-PSK symbols that compose the BCM codeword $\{S_1S_2S_3S_4\}$. In this example of natural binary mapping, the bits-to-symbol mapper 16 would transform code symbol triplets to 8-PSK modulation symbols using the following rule:

$$\text{modulation symbol number} = 4b_2 + 2b_1 + b_0$$

where the eight 8-PSK modulation symbols, indicated in the complex plane by the "x" marks, are consecutively numbered counter clockwise starting from the positive real axis as

shown in Fig. 3. The other conventional bits-to-symbol mapping, Gray code mapping, is similarly depicted in Fig. 4.

U.S. Patent No. 5,289,501 to Seshadri et al. describes a trellis coded modulation scheme and various bits-to-symbol mappings. U.S. Patent No. 5,168,509 to Nakamura et al. describes a multi-level QAM scheme and various mappings, including natural binary mapping, Gray code mapping, and "quadrant symmetry mapping".

From Figs. 3 and 4, it can be seen that for a modulation symbol identified by the triplet $\{b_2' \ b_1' \ b_0'\}$, there are four modulation symbols that differ in the bit b_0, i.e., that are identified by triplets having $b_0 \neq b_0'$. The probability of error in decoding that modulation symbol (BER) depends on the minimum Euclidean distance between the triplet $\{b_2' \ b_1' \ b_0'\}$ and the four triplets that have a different b_0. From these observations, it can be determined that the natural binary mapping offers the lowest probability of error for bit b_2 and increasing probability of error for bits b_1 and b_0, respectively. On the other hand, the Gray code mapping offers the lowest probability of error for bit b_0 and higher probability of error for bits b_1 and b_2. In general, the probability of error for one of the bits can be reduced only at the expense of increasing the probability of error for at least one of the other bits. In a coded modulation scheme, the probability of bit error is also affected by the choice of the component codes C_0, C_1, and C_2.

One of the main features of block coded modulation schemes is that each class of information is encoded according to a respective code, and hence unequal error protection of the classes can be readily achieved. The unequal error protection is useful for applications such as speech data, where all the bits are not equally important in a perceptual sense. The optimization of a coded modulation scheme involves choosing the component codes and the appropriate bits-to-symbol mapping that achieve the desired

performance specifications. For some component codes, neither the natural mapping or Gray code mapping yields the desired protection for the different classes.

In an application such as transmission of speech data in the American Digital Cellular System, which is specified by the IS-136 standard by the Telecommunications Industry Association (TIA) and the Electronic Industries Association (EIA), it is desirable for two classes of bits to have a significantly better BER performance than unencoded quadrature PSK (QPSK) and for one class of bits to have the same or only slightly better BER performance than unencoded QPSK. For this application, it has been found that both natural binary mapping and Gray code mapping do not provide adequate performance for the three classes of information when using block coded modulation. For the BCM scheme illustrated in Figs. 2 and 3, the natural binary mapping results in the BER of all three classes of bits being not appreciably different. Gray code mapping improves the performance of the Class 0 information at the cost of significant degradation of the other two classes. Since 6/7 of the information bits are represented by C_1 and C_2, this scheme is inadequate in terms of performance.

Moreover as noted above, natural binary mapping and Gray code mapping are usually used for constellations of modulation symbols that are uniformly spaced in the complex plane, although some variations of the Gray code mapping scheme for non-uniform constellations have been described. Nevertheless, such schemes with non-uniform constellations have practical and implementational disadvantages that make these systems hard to use.

A constellation of non-uniformly spaced modulation symbols for improving the BER of certain classes of bits is suggested in N. Seshadri et al., "Coded Modulation with Time Diversity, Unequal Error Protection and Low Delay for the Rayleigh Fading Channel", Proceedings of First Universal Conference on Portable and Mobile Communications pp. 283-287

(Sept. 29 - Oct. 2, 1992), which is cited above. This scheme has the disadvantage that, since some modulation symbols are closer together than when they are uniformly spaced, this constellation is more susceptible to phase, frequency, and timing-jitter errors. Phase errors arise from phase noise in frequency synthesizers and unsynchronized transmitter and receiver oscillators. Frequency errors arise from Doppler shifts and unsynchronized transmitter and receiver oscillators. Timing jitter arises from unsynchronized transmitter and receiver clocks.

These errors are manifest as rotations of the modulation symbol constellation in the complex plane, which can cause closer-together symbols to fall into the decision regions of their neighbors. This causes ambiguity that seriously impairs a communication system's ability to achieve timing, frequency, and phase synchronizations, which are necessary before decoding can occur. In view of the need for reliable synchronization, constellations of uniformly spaced modulation symbols have been preferred.

SUMMARY

One of the important considerations in a coded modulation scheme is the bits-to-symbol mapping, which has a significant impact on the overall error rate performance. This application describes bits-to-symbol mappings that can achieve different levels of error protection for different classes of information and simultaneously optimize the performance of the different classes.

In one aspect of Applicants' invention, a method of coded modulation of information includes the steps of encoding a stream of information bits according to a predetermined code, thereby generating a stream of code symbols, and mapping each code symbol onto a constellation of modulation symbols, thereby generating a stream of modulation symbols. The modulation symbols are assigned

locations in the constellation based on maximizing the product of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

Also, the modulation symbols may be assigned locations in the constellation by minimizing a metric given by:

$$M_{pd}=\sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

where N_p is a number of paths having differing product distances, P_{di} is the product distance of an i-th path, and N_i is a number of paths having the same product distance as the i-th path.

In another aspect of Applicants' invention, an apparatus for coded modulation of information includes a device for encoding a stream of information bits according to a predetermined code, thereby generating a stream of code symbols, and a device for mapping each code symbol onto a constellation of modulation symbols and generating a stream of modulation symbols. The modulation symbols are located in the constellation based on maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths. Also, the modulation symbols may be assigned locations in the constellation by minimizing a metric such as that given by the equation listed above.

In another aspect of Applicants' invention, a method of coded modulation of information includes the steps of encoding a plurality of streams of information elements, thereby forming a plurality of respective streams of coded bits; forming code symbols out of successive groups of the coded bits, wherein each group includes coded bits from all streams of coded bits; and mapping code symbols onto a constellation of modulation symbols, thereby generating a stream of modulation symbols, wherein the modulation symbols are assigned locations in the constellation based on

maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

Also, the modulation symbols may be assigned locations in the constellation by minimizing a metric given by the equation listed above. Each stream of information elements may be encoded according to a respective code, and the modulation symbols may be assigned locations in the constellation based on an optimized error rate performance for at least one of the streams of code symbols. Moreover, each stream of information elements may represent speech information and be encoded according to a respective block code.

In another aspect of Applicants' invention, an apparatus for coded modulation of information includes a device for encoding a plurality of streams of information elements and forming a plurality of respective streams of coded bits; a device for forming code symbols out of successive groups of coded bits, wherein each group includes coded bits from all streams of coded bits; and a device for mapping code symbols onto a constellation of modulation symbols and generating a stream of modulation symbols, wherein the modulation symbols are assigned locations in the constellation based on maximized products of non-zero Euclidean distances between code symbols along decoding trellis paths.

Also, the modulation symbols may be assigned locations in the constellation by minimizing a metric given by the equation listed above. Each stream of information elements may be encoded according to a respective code, and the modulation symbols may be assigned locations in the constellation based on an optimized error rate performance for at least one of the streams of code symbols. Moreover, each stream of information elements may represent speech information and be encoded according to a respective block code.

In another aspect of Applicants' invention, a method of coded modulation of information includes the steps of encoding a stream of information bits according to a predetermined code, thereby generating a stream of code symbols, and mapping each code symbol onto a constellation of modulation symbols, thereby generating a stream of modulation symbols. The code symbols are mapped according to a hybrid of a natural binary mapping and a Gray code mapping. Moreover, the hybrid may comprise a combination of two Gray code mappings that are rotated 45° with respect to each other.

In another aspect of Applicants' invention, an apparatus for coded modulation of information includes a device for encoding a stream of information bits according to a predetermined code, thereby generating a stream of code symbols, and a device for mapping each code symbol onto a constellation of modulation symbols and generating a stream of modulation symbols. The code symbols are mapped according to a hybrid of a natural binary mapping and a Gray code mapping, and the hybrid may comprise a combination of two Gray code mappings that are rotated 45° with respect to each other.

In another aspect of Applicants' invention, a method of coded modulation of information includes the steps of encoding a plurality of streams of information elements, thereby forming a plurality of respective streams of coded bits; forming code symbols out of successive groups of coded bits, wherein each group includes coded bits from all streams of coded bits; and mapping code symbols onto a constellation of modulation symbols, thereby generating a stream of modulation symbols, wherein the code symbols are mapped according to a hybrid of a natural binary mapping and a Gray code mapping.

Also, each stream of information elements may be encoded according to a respective code, and the modulation symbols may be located in the constellation based on an

optimized error rate performance for at least one of the streams of code symbols. Each stream of information elements may represent speech information and be encoded according to a respective block code, and the hybrid may comprise a combination of two Gray code mappings that are rotated 45° with respect to each other.

In another aspect of Applicants' invention, an apparatus for coded modulation of information includes a device for encoding a plurality of streams of information elements and forming a plurality of respective streams of coded bits; a device for forming code symbols out of successive groups of coded bits, wherein each group includes coded bits from all streams of coded bits; and a device for mapping code symbols onto a constellation of modulation symbols and generating a stream of modulation symbols, wherein the code symbols are mapped according to a hybrid of a natural binary mapping and a Gray code mapping.

Also, each stream of information elements may be encoded according to a respective code, and the modulation symbols may be located in the constellation based on an optimized error rate performance for at least one of the streams of code symbols. Each stream of information elements may represent speech information and be encoded according to a respective block code, and the hybrid may comprise a combination of two Gray code mappings that are rotated 45° with respect to each other.

In another aspect of Applicants' invention, a method of coded modulation of information, includes the steps of encoding a stream of information bits according to a predetermined code, thereby generating a stream of encoded information bits, and combining the stream of encoded information bits with a stream of unencoded information bits, thereby generating a stream of code symbols. Each code symbol is then mapped onto a constellation of modulation symbols, thereby generating a stream of modulation symbols. Code symbols whose unencoded

information bit is equal to a first value are mapped onto a first constellation of modulation symbols, and code symbols whose unencoded information bit is equal to a second value are mapped onto a second constellation of modulation symbols.

Also, modulation symbols in each of the first and second constellations may be assigned locations based on natural binary mapping. Alternatively, modulation symbols in each of the first and second constellations may be assigned locations based on Gray mapping. In yet another alternative embodiment, modulation symbols in each of the first and second constellations may be assigned locations in the respective first and second constellation based on maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

In another aspect of Applicants' invention, an apparatus for coded modulation of information includes a device for encoding a stream of information bits according to a predetermined code, thereby generating a stream of encoded information bits; a device for combining the stream of encoded information bits with a stream of unencoded information bits, thereby generating a stream of code symbols; and a device for mapping each code symbol onto a constellation of modulation symbols, thereby generating a stream of modulation symbols. Code symbols whose unencoded information bit is equal to a first value are mapped onto a first constellation of modulation symbols, and code symbols whose unencoded information bit is equal to a second value are mapped onto a second constellation of modulation symbols.

Also, modulation symbols in each of the first and second constellations may be assigned locations based on natural binary mapping. Alternatively, modulation symbols in each of the first and second constellations may be assigned locations based on Gray mapping. In yet another alternative, modulation symbols in each of the first and

second constellations may be assigned locations in the respective first and second constellation based on maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the invention will be understood by reading this description in conjunction with the drawings, in which:

Fig. 1 illustrates a transmitter that includes a BCM encoder;

Fig. 2 illustrates a BCM encoder;

Fig. 3 illustrates a natural binary mapping scheme for the BCM encoder of Fig. 2;

Fig. 4 illustrates a Gray code mapping scheme for the BCM encoder of Fig. 2;

Fig. 5 illustrates a BCM code trellis;

Fig. 6 illustrates a bits-to-symbol mapping based on product distances according to Applicants' invention; and

Figs. 7a, 7b, 7c illustrate a hybrid bits-to-symbol mapping according to Applicants' invention.

DETAILED DESCRIPTION

As described above, natural binary mapping and Gray code mapping may not yield the desired unequal error protection for a particular choice of component codes in a coded modulation scheme. Applicants have solved this problem and describe bits-to-symbol mappings that yield the ability to trade-off the performance between the different classes of bits while simultaneously optimizing the performance of each of the different information classes. Applicants' mapping schemes are advantageously implemented by an improved bits-to-symbol mapper 17' that would be used with the other components of a communication system such as that illustrated in Fig. 1, therefore a description of the general operation of such a system need not be repeated

here. It will be appreciated that such a device may be implemented as hard-wired logic circuitry of an application-specific integrated circuit (ASIC) or as an integrated digital signal processor. Of course it will be understood that an ASIC may include hard-wired logic circuitry that is optimal for performing a required function, which is an arrangement commonly selected when speed or another performance parameter is more important than the versatility of a programmable digital signal processor.

One bits-to-symbol mapper in accordance with Applicants' invention would implement a bits-to-symbol mapping that is based on maximizing the product of squared Euclidean distances (product distance) between the desired and an erroneous sequence of symbols that could be decoded under adverse channel conditions. This product distance based (PDB) mapping can be derived from consideration of a trellis representation of the coded modulation. Fig. 5 shows a trellis representation of a BCM scheme (see Figs. 1 and 2) comprising three component codes C_0 (rate 1/4 repetition code), C_1 (rate 3/4 single-parity-check code), and C_2 (rate 3/4 single-parity-check code) whose code symbols are mapped onto an 8-PSK constellation.

The trellis shown in Fig. 5 is a complete graphical representation of the BCM scheme as will be described below. The following description assumes that the speech coder has three bit classes that correspond to the bits' perceptual significance and that are protected by a BCM scheme accordingly, and the following description is in terms of 8-PSK. Nevertheless, it will be appreciated by those of ordinary skill in this art that the invention is not limited to this example. Applicants' invention is generally applicable to M-ary modulation schemes, such as M-ary PSK, for which the M modulation symbols would be addressed by M-tuples $\{b_{M-1}b_{M-2} \ldots b_1b_0\}$ that may be derived from one or more information streams. The invention is also generally applicable to coding schemes other than

block coding and to speech coders having other than three classes, and to other information sources.

Each possible BCM codeword corresponds to a respective path through the trellis illustrated in Fig. 5. In this example, the BCM component codes each have a block length of four, yielding four triplets of code symbols (addressing four 8-PSK symbols) for each BCM codeword that represents seven information bits. The number of information bits represented by each BCM codeword determines the number of BCM codewords that can possibly occur in that BCM code. In this example and since each information symbol can take only one of two values (0 and 1), the number of possible BCM codewords is $2^7 = 128$.

It can be seen that each path through the trellis, e.g., the path ABCDO, comprises a set of branches, e.g., AB, BC, CD, and DO. Each branch is labeled with the decimal value of a respective triplet $\{b_2b_1b_0\}$ that can be generated by the three component-code encoders 15 at each signalling interval. For example, the branches AB, BC, CD, and DO are labeled with the values 0, 0, 0, and 0, respectively. Thus in this example, the path ABCDO represents the BCM codeword comprising all zeroes, which is the result of mapping each of a sequence of four triplets $\{000\}$ onto a particular constellation of modulation symbols. As another example, the path ATPZO represents the BCM codeword comprising all sevens.

Decoding such a BCM codeword may be done using a maximum-likelihood technique like the well known Viterbi algorithm, which has also been modeled as a trellis. According to the Viterbi algorithm, each branch of the trellis represents a symbol and a metric is assigned to each branch that corresponds to the likelihood that the symbol represented by that branch is the actual transmitted symbol. One such metric is the squared Euclidean distance between a received signal and an estimated value of the signal, using the hypothesis that the symbol corresponding to that branch

was actually transmitted. Branches merge at each node in the trellis, and at each node the branch assigned the lowest valued metric is selected and used to update a node metric, or path metric. This is repeated through the trellis, and finally the path having the best path metric is selected. The information bits that are represented by the symbols represented by the selected path are produced as the decoded bits.

The product distance is defined as the product of the non-zero squared Euclidean distances of the symbols on an erroneous path through the trellis relative to the symbols on the correct path. The BER of such a coded modulation scheme depends, to a first approximation, on the product distance and the number of shortest error event paths. The shortest error event path, which is inversely proportional to the product distance along the error event, is a path that diverges from the correct path and re-merges with the correct path sooner than any other erroneous path. In accordance with one aspect of Applicants' invention, a bits-to-symbol mapping is chosen that maximizes the product distance, thereby minimizing the BER (optimizing the BER performance) for the corresponding class of information. Hence, this mapping scheme is called PDB bits-to-symbol mapping, which is illustrated by Fig. 6 for the exemplary BCM scheme.

To a first approximation and for a given signal to noise ratio, the BER can be minimized by minimizing the metric M_{pd} given by the following expression:

$$M_{pd}=\sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

where N_p is the number of paths of differing product distances, P_{di} is the product distance of the i-th path, and N_i is the number of paths with the same product distance as the i-th path. Applicants' PDB mapping assigns symbols to

the trellis branches such that the metric M_{pd} is minimized for each bit in the triplet $\{b_2b_1b_0\}$ identifying a modulation symbol. It will be appreciated, however, that the preceding expression for the metric M_{pd} is only one possible rule for assigning modulation symbols to trellis branches; there may be other rules that yield comparable performance. For example, $N_p=1$, $M_{pd}=N_1/P_{d1}$ could be used as a first order approximation based on the shortest error event. The shortest error event is most likely to occur, and is therefore a good rule to base the mapping on.

Referring again to the example trellis shown in Fig. 5, assume the sequence of modulation symbols S_0, S_0, S_0, S_0 is transmitted, corresponding to the triplet sequence {000} {000} {000} {000}. The corresponding (correct) path in the trellis is ABCDO. Considering the performance of bit b_1, the paths ABIDO, ABJDO, AFCDO, AGCDO, ABCLO and ABCMO differ in only two branches from the correct path and give rise to an error in the bit b_1. These are the shortest error event paths for bit b_1. The corresponding product distance on these branches is either $P_{d1} = | S_0 - S_4 |^2 | S_0 - S_4 |^2$ (for paths ABIDO, AFCDO, and ABCLO) or $P_{d2} = | S_0 - S_6 |^2 | S_0 - S_6 |^2$ (for paths ABJDO, AGCDO, and ABCMO).

For natural binary mapping (Fig. 3), $P_{d1} = 16$, $P_{d2} = 4$, and $M_{pd} = 0.9375$. For Gray code mapping (Fig. 4), the product distances are $P_{d1} = 11.65$, $P_{d2} = 4$, and $M_{pd} = 1.0075$. For Applicants' PDB mapping (Fig. 6), the product distances are $P_{d1} = 16$, $P_{d2} = 11.65$, and $M_{pd} = 0.4450$. It can be seen that for bit b_2 Applicants' PDB mapping minimizes M_{pd} and hence minimizes the BER for that bit. This has been confirmed by a computer simulation of a system using Applicants' PDB mapping.

The performance of bits b_0 and b_1 can be similarly optimized, but it must be noted that improving the BER performance of one class usually occurs at the expense of a decrease in performance of another class. The performances

of the classes can be traded-off in different ways, depending on the application.

For speech transmission in the American Digital Cellular system specified by the IS-136 standard, in which there are primarily two classes of information, Applicants' PDB mapping offers a better trade-off than Gray code mapping or natural binary mapping for the same coded modulation scheme. Natural binary mapping resulted in the BER of all three classes being not appreciably different. Gray code mapping improved the performance of 1/7 of the bits at the cost of degrading the performance of the other 6/7 of the bits to a level worse than that of natural binary mapping. PDB mapping resulted in 4/7 of the bits having better performance and 3/7 of the bits having worse performance relative to natural binary mapping.

In accordance with another aspect of Applicants' invention, a hybrid of natural binary mapping and Gray code mapping that can be used instead of PDB mapping is described below. This hybrid mapping is illustrated in Fig. 7a, from which it can be seen that the hybrid mapping comprises a combination of two Gray code mappings of a constellation of four modulation symbols (4-PSK) that are illustrated in Figs. 7b, 7c. The two mappings shown in Figs. 7b and 7c are rotated by 45 degrees with respect to each other, and each modulation symbol is identified by a doublet $\{b_2b_1\}$. These two constellations are superposed (yielding Fig. 7a) and distinguished by the third bit b_0, which together with the doublet $\{b_2b_1\}$ forms the triplet $\{b_2b_1b_0\}$ that identifies each 8-PSK symbol. The most heavily protected bit is mapped onto bit b_0; the least protected is mapped onto bit b_2; and the remaining bit is mapped onto bit b_1. In effect, the hybrid mapping of Fig. 7a is formed by using the third bit b_0 for selecting between the two mappings of Figs. 7b, 7c. The bit b_0 has the least Euclidean distance between a given modulation symbol and the other modulation symbols that

differ in the bit b_0, just as in the case of natural binary mapping.

The hybrid mapping allows a favorable trade-off between the performance of the different classes and yields better overall performance than the conventional natural binary mapping. Applicants' hybrid mapping, like the PDB mapping, is useful applications such as speech transmission in the American Digital Cellular System specified by the IS-136 standard. Hybrid mapping currently appears to be particularly useful for BCM schemes having one bit that is unencoded, such as BCM schemes having component code rates of [1/4, 3/4, 4/4] or [1/8, 6/8, 8/8] or [1/5, 4/5, 5/5]. The usefulness of such a BCM scheme lies in the fact that, with one unencoded bit, the overall information rate is increased, thereby allowing higher spectral efficiency.

It will be appreciated that Applicants' PDB mapping and hybrid mapping can be applied to other convolutional coding, trellis coding and block coding schemes by applying the principles of mapping bits such that the code distance properties in combination with the modulation symbol constellation are optimized. For example, a serial stream of bits may be split into two parallel streams, one of which may be encoded according to a rate 1/2 convolutional code and the other of which may remain unencoded. The resulting bit triplets can be mapped onto an 8-PSK symbol constellation, e.g., by Applicants' hybrid mapping. For another example, the serial stream may be split into three information streams that are respectively encoded according to three different convolutional codes having rate 1/4, rate 3/4, and rate 3/4, respectively. The encoded bits can be mapped onto an 8-PSK constellation using one of the mappings described above, e.g., PDB mapping.

It will be appreciated by those of ordinary skill in the art that this invention can be embodied in other specific forms without departing from its essence. The embodiments described above are therefore to be considered

illustrative and not restrictive. The scope of the invention is defined by the following claims rather than the foregoing description, and all changes that come within the meaning and range of equivalents of the claims are intended to be embraced therein.

WHAT IS CLAIMED IS:

1. A method of coded modulation of information, comprising the steps of:

encoding a stream of information bits according to a predetermined code, thereby generating a stream of code symbols; and

mapping each code symbol onto a constellation of modulation symbols, thereby generating a stream of modulation symbols,

wherein the modulation symbols are assigned locations in the constellation based on maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

2. The method of claim 1, wherein the modulation symbols are assigned locations in the constellation by minimizing a metric given by:

$$M_{pd}=\sum_{i=1}^{N_p}\frac{N_i}{P_{di}}$$

where N_p is a number of decoding trellis paths having differing product distances, P_{di} is the product distance of an i-th decoding trellis path relative to a desired decoding trellis path, and N_i is a number of decoding trellis paths having the same product distance as the i-th decoding trellis path.

3. An apparatus for coded modulation of information, comprising:

means for encoding a stream of information bits according to a predetermined code, thereby generating a stream of code symbols; and

means for mapping each code symbol onto a constellation of modulation symbols and generating a stream of modulation symbols,

wherein the modulation symbols are located in the constellation based on maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

4. The apparatus of claim 3, wherein the modulation symbols are assigned locations in the constellation by minimizing a metric given by:

$$M_{pd}=\sum_{i=1}^{N_p}\frac{N_i}{P_{di}}$$

where N_p is a number of decoding trellis paths having differing product distances, P_{di} is the product distance of an i-th decoding trellis path relative to a desired decoding trellis path, and N_i is a number of decoding trellis paths having the same product distance as the i-th decoding trellis path.

5. A method of coded modulation of information, comprising the steps of:

encoding a plurality of streams of information elements, thereby forming a plurality of respective streams of coded bits, wherein each stream of information elements is encoded according to a respective code;

forming code symbols out of successive groups of coded bits, wherein each group includes coded bits from all streams of coded bits; and

mapping code symbols onto a constellation of modulation symbols, thereby generating a stream of modulation symbols, wherein the modulation symbols are assigned locations in the constellation based on maximized

products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

6. The method of claim 5, wherein the modulation symbols are assigned locations in the constellation by minimizing a metric given by:

$$M_{pd}=\sum_{i=1}^{N_p}\frac{N_i}{P_{di}}$$

where N_p is a number of decoding trellis paths having differing product distances, P_{di} is the product distance of an i-th decoding trellis path relative to a desired decoding trellis path, and N_i is a number of decoding trellis paths having the same product distance as the i-th decoding trellis path.

7. The method of claim 5, wherein each stream of information elements is encoded according to a respective code, and the modulation symbols are assigned locations in the constellation based on an optimized error rate performance for at least one of the streams of code symbols.

8. The method of claim 5, wherein each stream of information elements represents speech information and is encoded according to a respective block code.

9. An apparatus for coded modulation of information, comprising:

means for encoding a plurality of streams of information elements and forming a plurality of respective streams of coded bits, wherein each stream of information elements is encoded according to a respective code;

means for forming code symbols out of successive groups of coded bits, wherein each group includes coded bits from all of the streams of coded bits; and

means for mapping code symbols onto a constellation of modulation symbols and generating a stream of modulation symbols, wherein the modulation symbols are assigned locations in the constellation based on maximized products of non-zero Euclidean distances between code symbols along decoding trellis paths.

10. The apparatus of claim 9, wherein the modulation symbols are assigned locations in the constellation by minimizing a metric given by:

$$M_{pd}=\sum_{i=1}^{N_p} \frac{N_i}{P_{di}}$$

where N_p is a number of decoding trellis paths having differing product distances, P_{di} is the product distance of an i-th decoding trellis path, and N_i is a number of decoding trellis paths having the same product distance as the i-th decoding trellis path.

11. The apparatus of claim 9, wherein each stream of information elements is encoded according to a respective code, and the modulation symbols are assigned locations in the constellation based on an optimized error rate performance for at least one of the streams of code symbols.

12. The apparatus of claim 9, wherein each stream of information elements represents speech information and is encoded according to a respective block code.

13. A method of coded modulation of information, comprising the steps of:

encoding a stream of information bits according to a predetermined code, thereby generating a stream of code symbols; and

mapping each code symbol onto a constellation of modulation symbols, thereby generating a stream of modulation symbols,

wherein the code symbols are mapped according to a hybrid of a natural binary mapping and a Gray code mapping.

14. The method of claim 13, wherein the hybrid comprises a combination of two Gray code mappings that are rotated 45° with respect to each other.

15. An apparatus for coded modulation of information, comprising:

means for encoding a stream of information bits according to a predetermined code, thereby generating a stream of code symbols; and

means for mapping each code symbol onto a constellation of modulation symbols and generating a stream of modulation symbols,

wherein the code symbols are mapped according to a hybrid of a natural binary mapping and a Gray code mapping.

16. The apparatus of claim 15, wherein the hybrid comprises a combination of two Gray code mappings that are rotated 45° with respect to each other.

17. A method of coded modulation of information, comprising the steps of:

encoding a plurality of streams of information elements, thereby forming a plurality of respective streams of coded bits, wherein each stream of information elements is encoded according to a respective code;

forming code symbols out of successive groups of the coded bits, wherein each group includes coded bits from all of the streams of coded bits; and

mapping the code symbols onto a constellation of modulation symbols, thereby generating a stream of modulation symbols, wherein the code symbols are mapped according to a hybrid of a natural binary mapping and a Gray code mapping.

18. The method of claim 17, wherein each stream of information elements is encoded according to a respective code, and the modulation symbols are located in the constellation based on an optimized error rate performance for at least one of the streams of code symbols.

19. The method of claim 17, wherein each stream of information elements represents speech information and is encoded according to a respective block code.

20. The method of claim 17, wherein the hybrid comprises a combination of two Gray code mappings that are rotated 45° with respect to each other.

21. An apparatus for coded modulation of information, comprising:

means for encoding a plurality of streams of information elements and forming a plurality of respective streams of coded bits, wherein each stream of information elements is encoded according to a respective code;

means for forming code symbols out of successive groups of the coded bits, wherein each group includes coded bits from all of the streams of coded bits; and

means for mapping code symbols onto a constellation of modulation symbols and generating a stream of modulation symbols, wherein the code symbols are mapped

according to a hybrid of a natural binary mapping and a Gray code mapping.

22. The apparatus of claim 21, wherein each stream of information elements is encoded according to a respective code, and the modulation symbols are located in the constellation based on an optimized error rate performance for at least one of the streams of code symbols.

23. The apparatus of claim 21, wherein each stream of information elements represents speech information and is encoded according to a respective block code.

24. The apparatus of claim 21, wherein the hybrid comprises a combination of two Gray code mappings that are rotated 45° with respect to each other.

25. A method of coded modulation of information, comprising the steps of:

encoding a stream of information bits according to a predetermined code, thereby generating a stream of encoded information bits;

combining the stream of encoded information bits with a stream of unencoded information bits, thereby generating a stream of code symbols; and

mapping each code symbol onto a constellation of modulation symbols, thereby generating a stream of modulation symbols,

wherein code symbols whose unencoded information bit is equal to a first value are mapped onto a first constellation of modulation symbols, and code symbols whose unencoded information bit is equal to a second value are mapped onto a second constellation of modulation symbols.

26. The method of claim 25, wherein modulation symbols in each of the first and second constellations are assigned locations based on natural binary mapping.

27. The method of claim 25, wherein modulation symbols in each of the first and second constellations are assigned locations based on Gray mapping.

28. The method of claim 25, wherein modulation symbols in each of the first and second constellations are assigned locations in the respective first and second constellation based on maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

29. An apparatus for coded modulation of information, comprising:

means for encoding a stream of information bits according to a predetermined code, thereby generating a stream of encoded information bits;

means for combining the stream of encoded information bits with a stream of unencoded information bits, thereby generating a stream of code symbols; and

means for mapping each code symbol onto a constellation of modulation symbols, thereby generating a stream of modulation symbols,

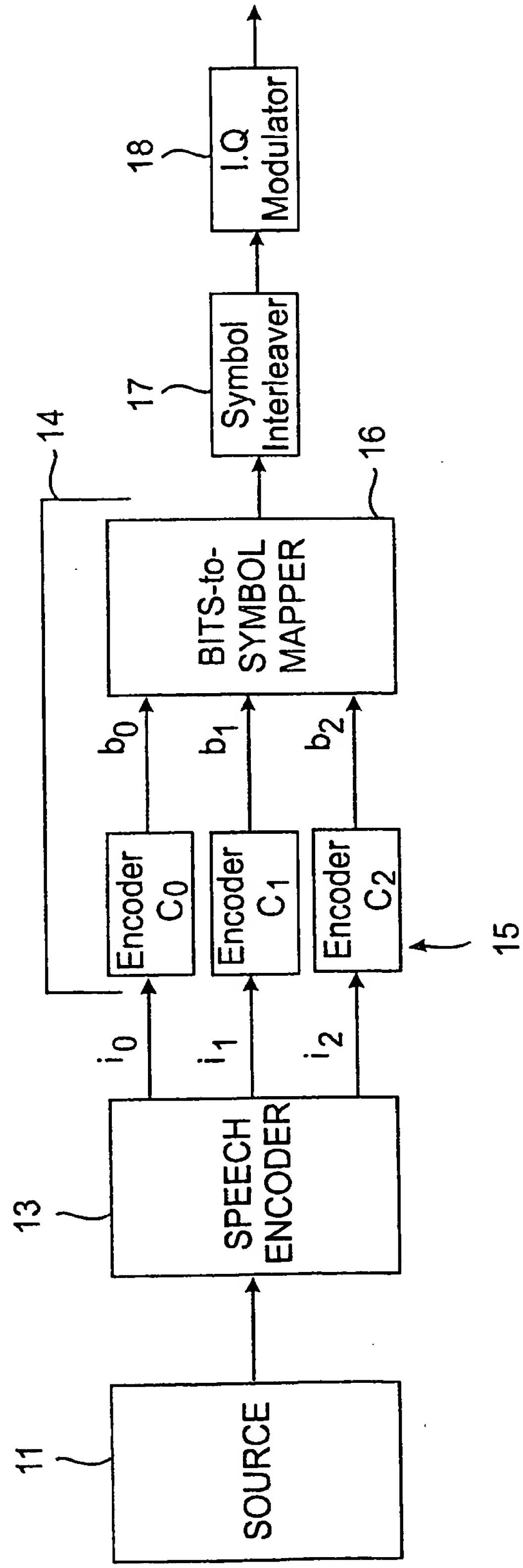
wherein code symbols whose unencoded information bit is equal to a first value are mapped onto a first constellation of modulation symbols, and code symbols whose unencoded information bit is equal to a second value are mapped onto a second constellation of modulation symbols.

30. The apparatus of claim 29, wherein modulation symbols in each of the first and second constellations are assigned locations based on natural binary mapping.

31. The apparatus of claim 29, wherein modulation symbols in each of the first and second constellations are assigned locations based on Gray mapping.

32. The apparatus of claim 29, wherein modulation symbols in each of the first and second constellations are assigned locations in the respective first and second constellation based on maximized products of non-zero squared Euclidean distances between code symbols along decoding trellis paths.

Fig. 1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Encoder C_1
Encoder C_2
14
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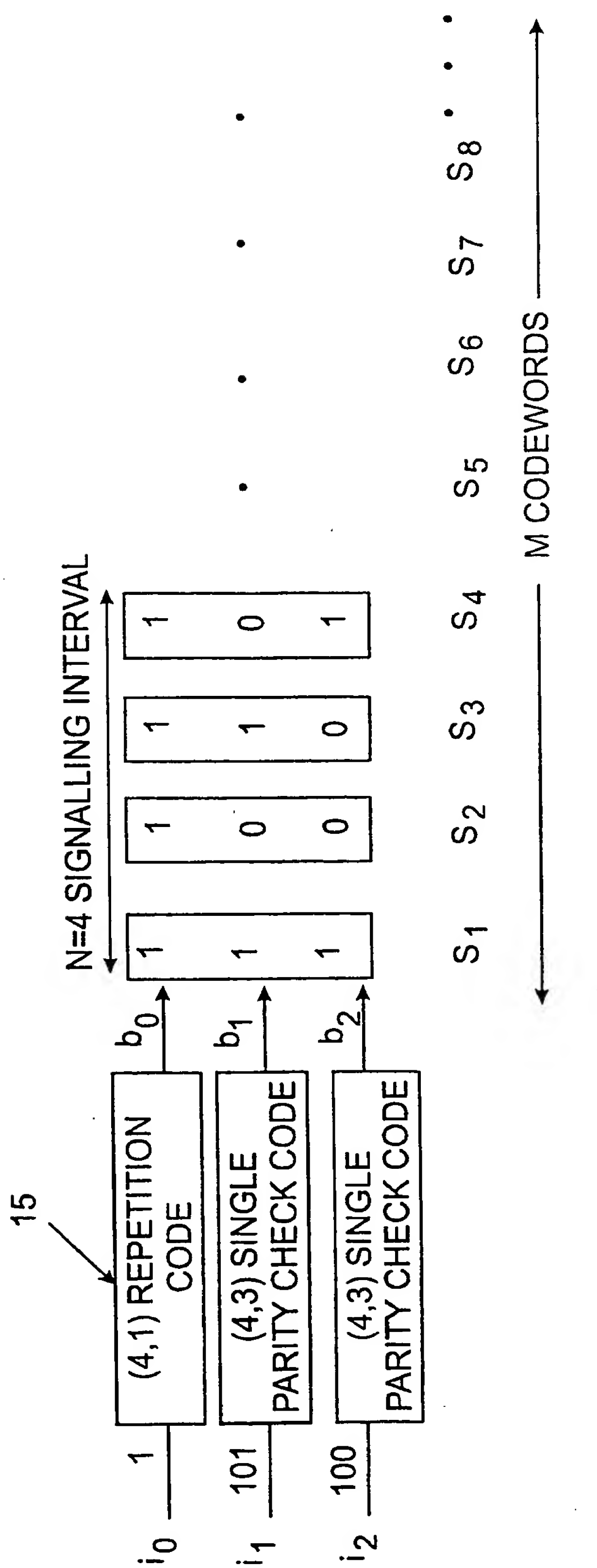
b_0
b_1
b_2
BITS-to-SYMBOL MAPPER
16
Symbol Interleaver
17
I.Q Modulator
18

Fig. 2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i_1
i_2
1
101
100
15
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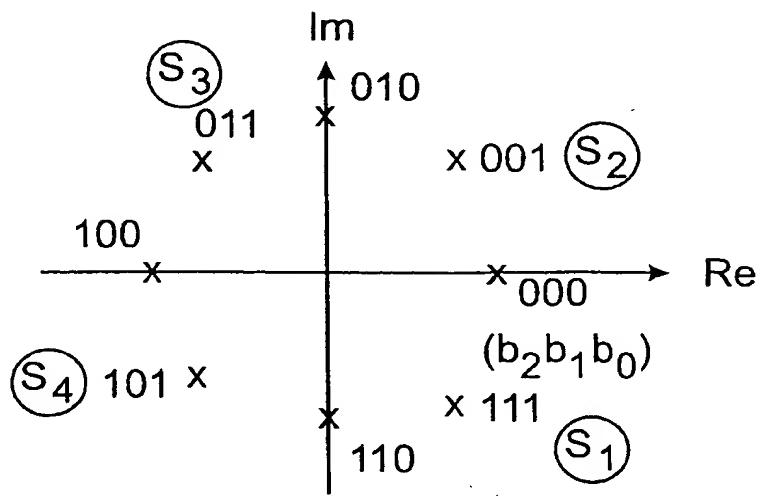
(4,3) SINGLE PARITY CHECK CODE
(4,3) SINGLE PARITY CHECK CODE
b_0
b_1
b_2
N=4 SIGNALLING INTERVAL
S_1 S_2 S_3 S_4 S_5 S_6 S_7 S_8
M CODEWORDS

Fig. 3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S_4

Fig. 4

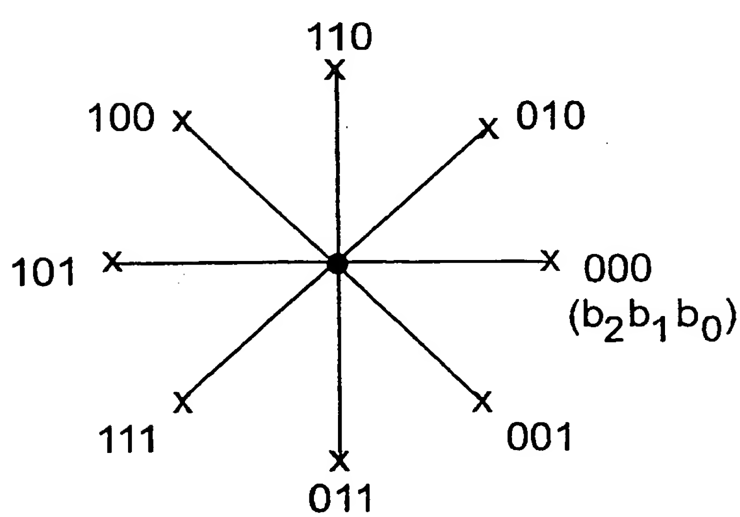
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Fig. 5

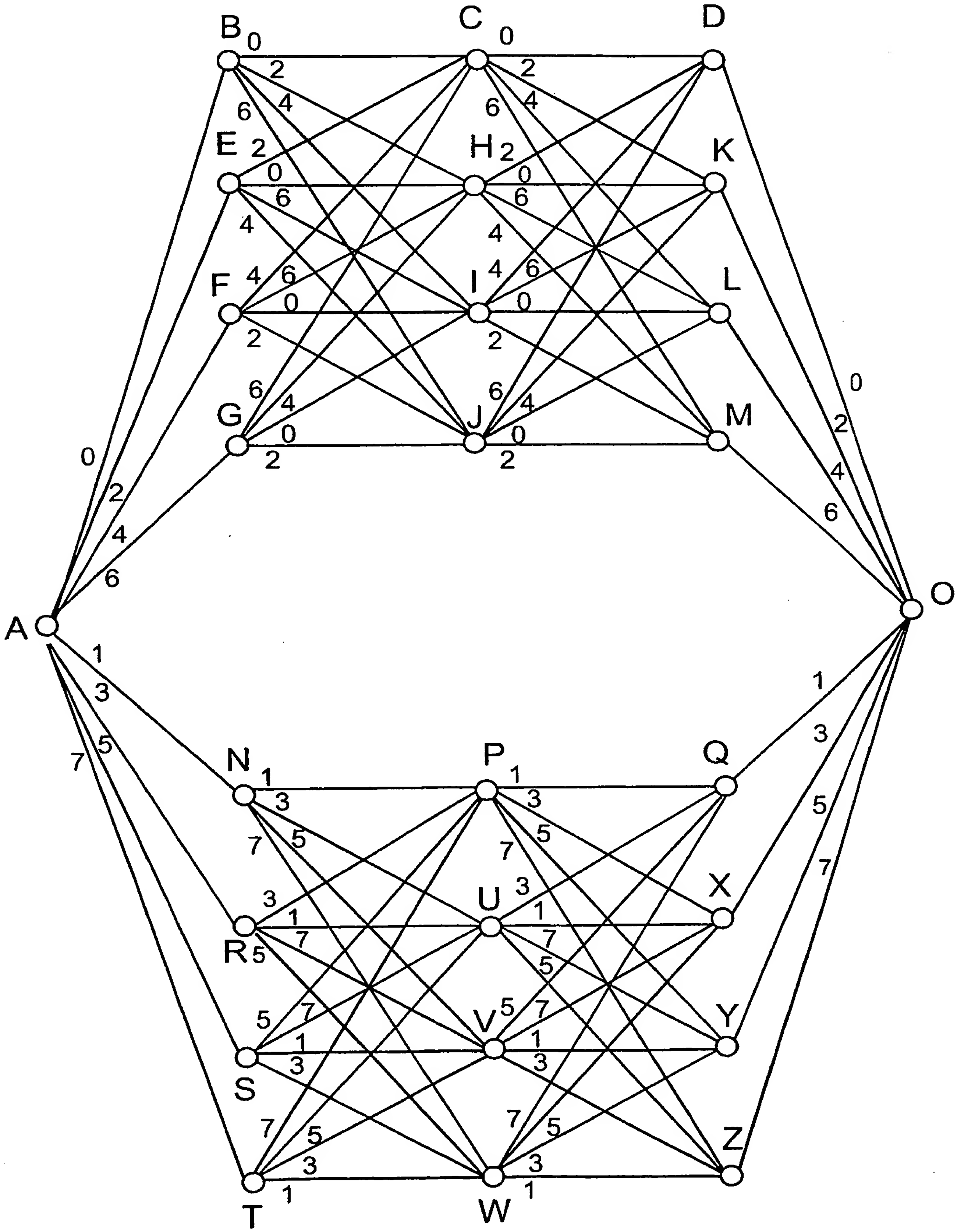
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Fig. 6

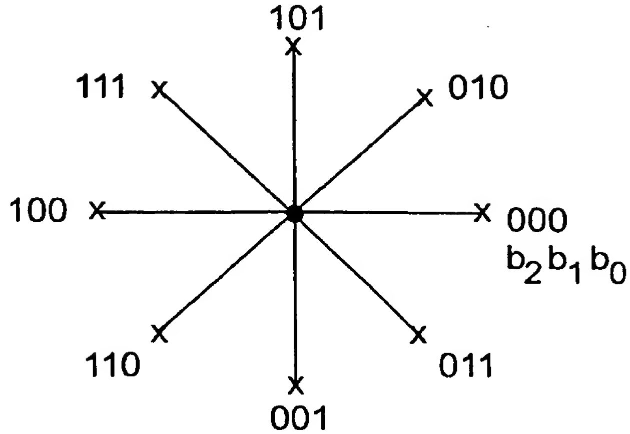


Fig. 7c

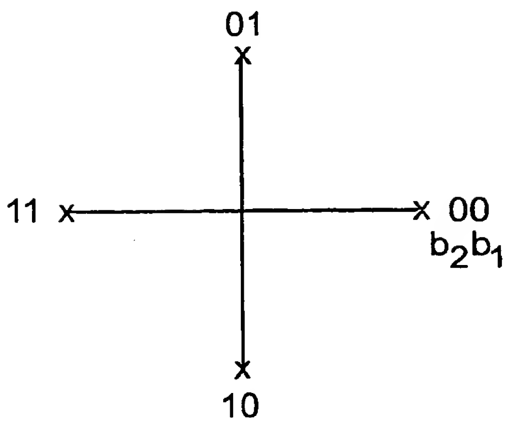


Fig. 7b

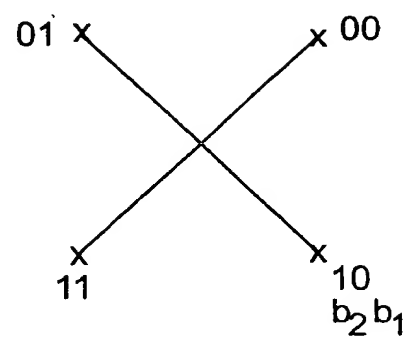
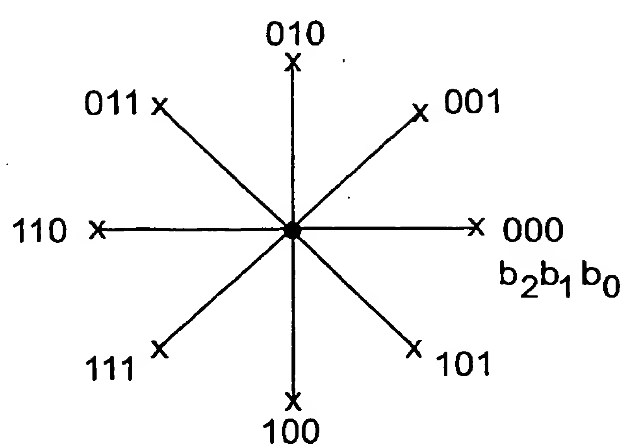


Fig. 7a



INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/19885

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04L27/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 544 463 A (AT&T) 2 June 1993 cited in the application see column 2, line 24 - line 29 see column 2, line 50 - column 3, line 5 see column 6, line 10 - line 15 see column 7, line 31 - line 37 see column 8, line 30 - line 41 see column 9, line 50 - line 54 see figure 5 ---	1-32
X	EP 0 633 680 A (ERICSSON) 11 January 1995 see page 3, line 30 - line 44 see page 6, line 37 - page 7, line 14 see page 7, line 43 - page 8, line 35 --- -/--	1-12

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 January 1999	01/02/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Scriven, P

1

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Inter. onal Application No
PCT/US 98/19885

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	JIANTIAN WU, SHU LIN: "Multilevel trellis MPSK modulation codes for the Rayleigh fading channel" IEEE TRANSACTIONS ON COMMUNICATIONS, vol. 41, no. 9, September 1993, pages 1311-1318, XP000396694 see page 1311, right-hand column, paragraph 3 - page 1312, left-hand column, paragraph 1 see page 1312, left-hand column, paragraph 3 see page 1312, right-hand column, paragraph 1 ---	1-12
X	EP 0 536 948 A (AT&T) 14 April 1993 see column 4, line 29 - line 51 ---	1-12
X	LEONARDO ET AL.: "Multidimensional M-PSK trellis codes for fading channels" IEEE TRANSACTIONS ON INFORMATION THEORY, vol. 42, no. 4, July 1996, pages 1093-1108, XP002071021 NEW YORK, US see page 1093, left-hand column, paragraph 2 - right-hand column, paragraph 1 see page 1095, left-hand column, paragraph 1 ---	1-12
X	JIAN LIU ET AL.: "LSB coded 8PSK signals" IEEE TRANSACTIONS ON COMMUNICATIONS, vol. 43, no. 2/4, February 1995, pages 151-153, XP000506542 see figures 2-4 see page 151, left-hand column, paragraph 2 - paragraph 3 -----	13-32

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..iformation on patent family members

Inter: nal Application No
PCT/US 98/19885

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EP 0536948 A	14-04-1993	US 5301209 A	05-04-1994
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